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Lunar Composite Production: Interim Report

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Summary

A minimally processed composite material derived from lunar soil and possessing tensile strength is described. Laboratory work conducted during June and July of 1986 and the direction of future work are discussed.

Introduction

The National Commission on Space suggests "Research to pioneer the use, in construction and manufacturing, of space materials that do not require chemical separation, for example, lunar glasses and metallic iron concentrated in the lunar fines."[1]

Lunar glasses can be produced simply by melting certain kinds of regolith (lunar soil).[a] Like terrestrial glasses, they have considerable strength in tension and compression,[b] but are too brittle to be safely used in construction. Under moderate tensile loads, cracks of less than a millimeter depth propagate spontaneously at the speed of sound.[2] That is why a dropped dish cracks. While glass with an unflawed surface exhibits considerable tensile strength, there is no inspection method which can tell whether any given surface is, in fact, flawed. Therefore, bulk glass (like bulk rock) is an inherently unsafe structural material if subject to tensile stresses.

A material which cannot tolerate tensile stresses cannot be used for beams.[c]

Architecturally, its applications are restricted to thick walls, columns, domes, and arches (although flying buttresses can alleviate the severity of these restrictions to some extent). Structures employing only these forms are typically massive and require considerable labor to erect; in part for this reason stone architecture has been largely restricted to public buildings on Earth. There is no reason to believe that costs would be less on the lunar surface.

Two methods of avoiding the crack propagation failure mode[d] are of interest. One is pre-stressing. A glass plate, for example, can be solidified rapidly by air blast. If the solidification is only partial, an outside shell forms around a molten center. When the center cools, it contracts, putting itself in tension and the shell in compression. The center part, in tension, has to all intents and purposes an unflawed surface. The outer part, in compression and thus insensitive to cracks, protects the inner part. This pre-stressed system is quite strong and tough, but will release its stress energy suddenly if a crack does manage to penetrate the compressed region. The energy release is often enough to reduce the system to glass chips.

A second method of avoiding crack propagation is to make the unit glass structure smaller than the critical crack length. This is done by forming glass into long strands of ten to twenty microns thickness and several centimeters length. The glass fibers are held together by a matrix, and thus are one component of a composite material. The most commonly encountered material of this sort is fiberglass, which typically uses epoxy resin for the matrix.

The glass fiber composite appeared most suitable for initial investigation, primarily on grounds of safety. A glass matrix composite is not subject to catastrophic failure when its design stresses are exceeded, whereas a pre-stressed system (including, interestingly enough, pre-stressed concrete in compression) is.[e]

Microstructure

A lunar derived glass fiber composite cannot very well use epoxy as a matrix; neither epoxy nor its component element carbon can be readily found on the lunar surface. We intend to produce, not fiberglass, but rather an analog to fiberglass. We are not the only group doing this; Goldsworthy's group at the Space Studies Institute is pursuing development of a similar material.[3]

Strictly speaking, the proposed composite is three phase: glass, metal, and vacuum. The microstructure should look like a mass of sticky cotton. The threads will be glass, the glue will be metal, and the spaces between threads vacuum. The metals will be sticky because they will have free surfaces, created and maintained in high vacuum.[f] The threads will stick together where they touch; they will be unsupported between intersections.

The incentive for studying a three phase material is potential reduction of matrix volume fraction. To obtain Lunar metal requires more processing than to obtain lunar regolith;. the less metal required, the less labor and capital required to make the composite. Should it be necessary, a more conventional matrix could be obtained by increasing the metal fraction. At the limit, the glass fibers would no longer touch each other significantly often, and would act as an extender for lunar derived metal (at some cost in energy: the metal would have to be vaporized, or at least melted, before mixing with the glass).

The tensile strength of this material should depend on the cross-sectional area fraction which is glass (and the resistance to delamination). The compressive strength should depend on the force required to initiate bending in fibers between junctions (which must therefore be rather tightly spaced). The ultimate compressive stress may be fairly low (5E3psi),[g] but this does not preclude its use in beams. The corresponding stress for commercial pine beams is much lower (250 psi).[h]

A long shot, but an interesting one, is a glass / vacuum composite. It is possible that

newly drawn glass fibers will vacuum weld without metal coating. If so, the strength of the glass / glass bonds could be increased by heat treatment. While this composite would probably not be as strong as a glass / metal / vacuum composite, it may be comparable to wood in strength. If so, it would still be useful for light duty applications.

It would have the immense advantage of being fabricable entirely from Apollo 16 regolith,[i] with no preprocessing whatsoever. Glass / metal / vacuum composite production costs appear likely to be dominated by metal mining and extraction. While metal related costs could be greatly reduced by using byproducts of a lunar oxygen process as composite feedstock,[j] these byproducts may at times be unavailable. If composite production is run as a solo process, costs might be significantly reduced by electing to produce a glass / vacuum composite.

Previous Work

As part of a Universities Space Research Association (USRA) supported course on Advanced Mission Design, a group at Clemson specified a method of converting Apollo 16 bulk regolith into glass fibers. The method is based on the commercial Tel disk process, and is shown in Figure 1. It relies on introducing molten regolith into a rapidly rotating shallow bowl (called a disk) with perforated sides. Centrifugal force extrudes glass through the perforations as fibers, which break free from the disk upon reaching a length of several centimeters. The fibers are thinly metal coated by vapor deposition before landing on collection surfaces. Glass mat accumulating on the collection surfaces should form a glass / metal / vacuum composite of the kind discussed above.

Predictions of the composite's properties must be experimentally tested before they can be accepted. The Clemson group has, during June and July of 1986, done preliminary work required to fabricate and test composites of this kind.

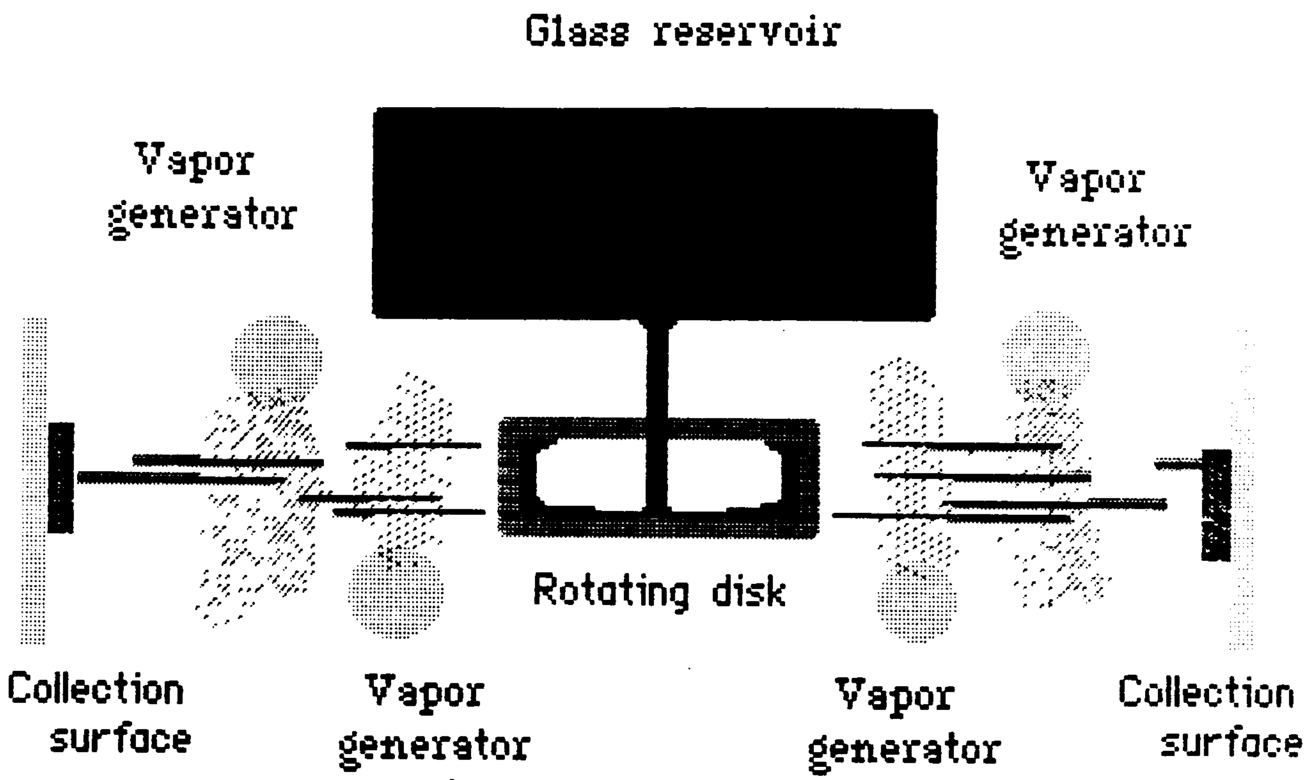

Figure 1. Disk fiberization.

Preparation for Laboratory Work

The rotating disk process is not suitable for laboratory use. Accordingly, a method called the "textile process," shown in Figure 2, was selected. The textile process relies on an glass reservoir with a nozzle (called a bushing) in its bottom. Glass flowing through the bushing is caught and wound onto a reel at high speed (about 3 meters / second). It can be metal coated while between the bushing and the reel.

The laboratory equipment is designed to pull about 30 kilometers of a 30E-6 meter diameter fiber from the reservoir, metal coat it, and wind it around a sample collecting reel in the form of cigarette sized samples. The entire operation should take about 3 hours. Samples will be subject to material properties tests.

The overall textile process system consists of three parts: a glass melting furnace,[k] capable of 1600° C and containing a platinum reservoir, a computer controlled[l] takeup reel,[m] capable of producing 6 test samples of about 6 cm length by 0.6 cm diameter, and a calcium vapor generator,[n] capable of vaporizing up to 100 grams of calcium over a six hour interval at about 850° C. All components are to operate in vacuum of 8E-5 torr.[p]

Clear bottle glass is to be used for equipment checkout and first approximation composite property determination. Apollo 16 regolith simulant (assembled from bulk chemicals) will be used after the system is seen to work well with bottle glass.[q]

Calcium is selected as the metal for glass coating because it can be made to sublimate at a fairly low temperature in vacuum[r] and could be extracted from lunar regolith.

Laboratory work

Of these three components, only the reel has been successfully and completely tested in vacuum.

The calcium vapor generator has been tested, and molecular flow of calcium in what appears to

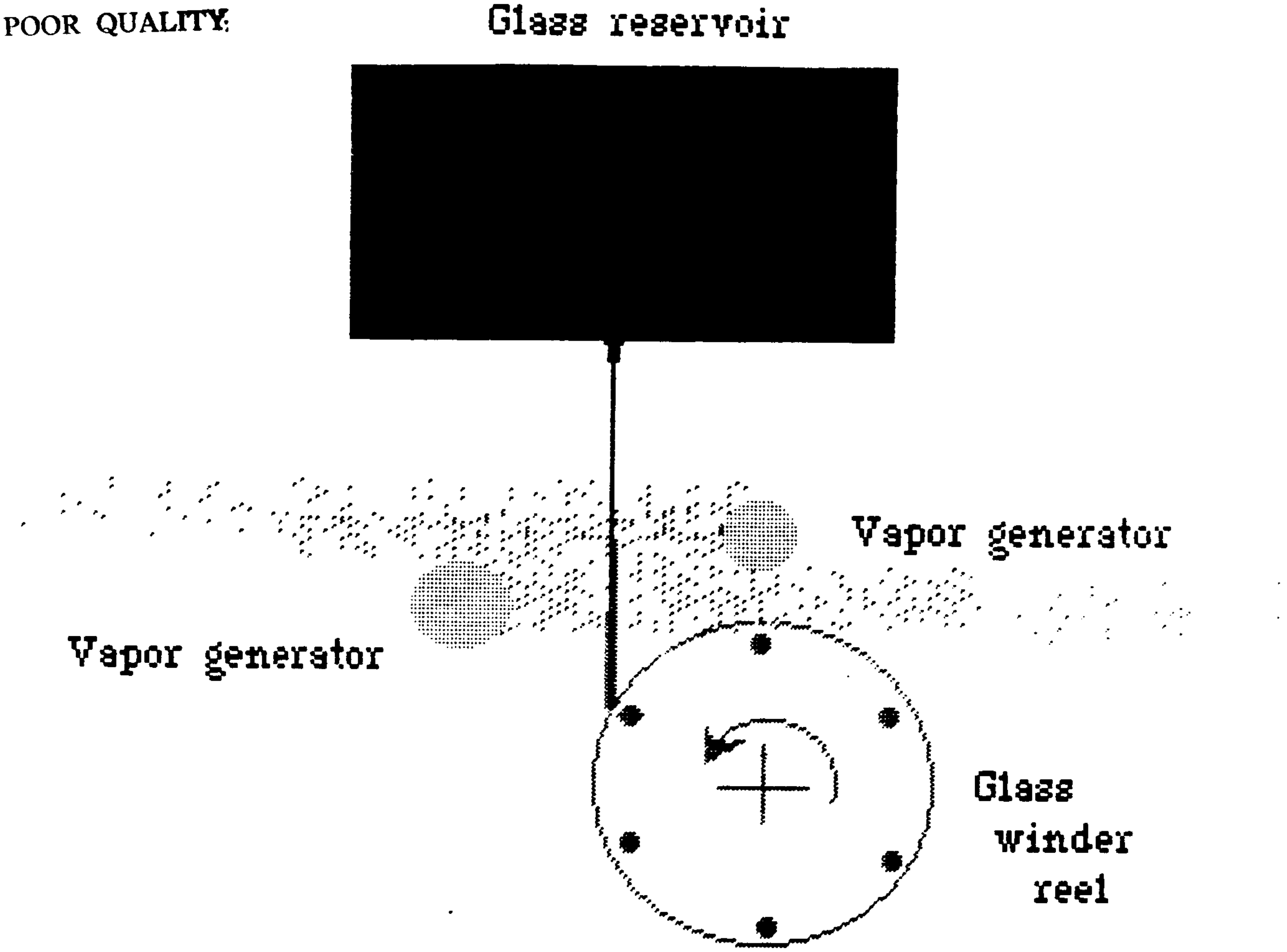

Figure 2. Textile Process

be adequate volume has been demonstrated. However, the generator itself was severely damaged during the test run, and repair proved uneconomical. The calcium vapor nozzle was apparently cool enough to permit condensation inside the orifice; when the orifice become plugged, vapor escaped through gaps around the endcaps in enough volume to damage heating coils and surrounding refractory.[v] It should be noted that this escape posed no hazard to any person, and that the vacuum chamber was not damaged in any way. A calcium vapor generator not susceptible to these failures has been conceptually designed.

The furnace reaches rated temperature (1200° C) in air and in vacuum. The glass melts properly in air. We have succeeded in drawing fibers from Apollo 16 regolith simulant.[s]

First, we learned that a crucible bottom of pure platinum becomes wetted by molten glass; this inhibits fiber formation. We reduced wetting to acceptable levels by alloying the platinum with a few percent gold.[t] We next found that our empirical formula for nozzle design[u] required adjustment for the small flow rates we wanted. Our data lead us to believe that a nearly stationary boundary layer of about 0.5 mm forms on platinum surfaces. This reduces effective bushing diameter by about 1 mm. Accordingly, we added 1 mm to our calculated bushing diameter in an attempt to increase flow to the desired amount. This change produced the desired flow for bottle glass.

After establishing that the furnace / reel combination could fiberize bottle glass, pulling rate was increased until 30E-6 meter diameter fibers were obtained. The reel was next moved from side to side (translated) by the translation motor under computer control.

This equipment was used to determine flow rate for bottle glass at several temperatures. From this, and a knowledge of bottle glass viscosity, it should be possible to determine the geometric constant D^4/L in our empirical flow formula for the crucible.

We next attempted to fiberize Apollo 16 simulant.[s] A frit of glassy fragments had been prepared at Clemson. The crucible was filled

with this frit and heated in air to 1250°C, at which point the melted simulant's viscosity permitted fiberization. We were able to produce fibers of 30E-6 meter diameter with a pulling rate of about 9 feet per second.

To our knowledge, this is the first time simulated lunar material has been fiberized using the textile process. While the fibers produced have not been formally tested, they seem somewhat stronger and more rigid than bottle glass. Produced on a large scale, they could be used with epoxy matrix to make standard fiberglass.

Fibers were pulled at three different temperatures to establish flow rate. From this it should be possible to deduce a viscosity vs. temperature relation for the lunar simulant.

Conclusion

To date, the project has taken up one semester of planning and nine weeks of laboratory work. The laboratory work will not be complete this summer; we intend to return to Clemson, think and plan some more, and complete the laboratory work in 1987.

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Footnotes

[a] Ideal fiberglass should contain, by weight percent:
SiO_2: 60; AL_2O_3: 5; CaO/MgO: 35; FeO/TiO_2: 0.
Lunar regolith at the Apollo sites 11, 12, 14, 15, and 16 has average weight percents of:
SiO_2: 45.6; AL_2O_3: 17.8; CaO/MgO: 21.0;
FeO/TiO_2: 14.5 (from data in Rose).[5]
It is a bit long on SiO_2 and Al and Fe/Ti oxides.

[b] In fact the ultimate tensile strength of common bottle glass, made into fibers, is 200 kpsi, as compared to 224 kpsi for bridge wire steel. From Table 1-115, Bolz.[7]

[c] A beam supported at both ends and loaded by a weight at midspan is in compression above the neutral axis and in tension below the neutral axis. While more complicated loadings are usually encountered, typically some sections of any beam are in compression and others in tension. Ropes, in contrast, are in tension throughout, and bricks in compression throughout.

[d] A third method is to alter the ceramic material so that free surface energy is drastically increased, or so that cracks tend to branch when propagated. Both strategies increase the critical crack length, but neither can be made from "minimally processed material," and are accordingly outside the scope of this project.

[e] The main drawback of fiberglass is not its ultimate tensile strength, but rather its flexibility. Glass fibers are as strong as steel (those with perfect surfaces are considerably more so), but are also more flexible. Glass typically has a Young's Modulus (E) of 11 Mpsi, whereas steel has an E of about 30 Mpsi. The same load will produce about three

times the deformation for a glass as a steel structure, if the geometries are identical.

[f] Pressure at the lunar surface is 1E-14 torr. The vacuum chamber used this summer (Chamber P, Bldg. 33, NASA Johnson Space Center, Houston, TX) could provide a vacuum of 8E-5 torr with textile process equipment inside, but this vacuum is thought to be sufficient to permit vacuum welding of newly created free surfaces.

[g] From an application of Rankine's formula, estimating phi using Ritter's Rational Formula, as described in Eshbach,[4] pg. 528 ff. Ultimate compressive strength of 160E3 psi, and E of 10.4E6 psi assumed are for silica glass, as given in Table 1-120, Bolz.[7] An l/d ration of 20 is assumed.

[h] Table 1-124, Bolz.[7]

[i] Composition of Apollo 16 regolith by weight percent is: SiO_2: 44.9; AL_2O_3: 26.7; CaO/MgO: 21.6; FeO/TiO_2: 6.1.[5] Variations by weight percent are: SiO_2: 0.7; AL_2O_3: 2.9; CaO/MgO: 3.9; FeO/TiO_2: 2.4.[5,6]

[j] Lunar oxygen production processes break up selected metal oxides into oxygen and metal byproducts. If the selected metals are not desirable in glass (iron, titanium, and excess aluminum oxides, for example) regolith discarded from the process may be better suited to glass formation than raw regolith. Any metal byproducts will be useful as matrix.

[k] The furnace is custom designed. It is a hexagonal cylinder, 6" wide sides (outer dimensions), 1.5" thick outer walls, 4.5" top, 3.0" bottom, kaowool (alumina silicate) construction. An additional molybdenum foil infrared shield (from GTE Sylvania) is used in vacuum. Heating is by 6 bayonet glowbars, 12 inch height, 5 ohms nominal resistance (from I^2R). A PID controller is used to control temperature. Normal power consumption at 1200° C is about 2 kw.

[l] The computer is an NCR Mk. IV with 256K bytes of memory running LMI Forth under NCR DOS 2.1. The interface board is a Metrabyte PIO board, which uses an Intel parallel I/O chip to send step and direction information. The stepper motor control board was fabricated by group members.

[m] The reel is rotated by a dc motor, and moved transversely by a stepper motor. It has been tested at 408 rpm, corresponding to a 3.4 meter / second pulling rate.

[n] The calcium generator was custom designed. It consisted of a containment vessel and a furnace. The containment vessel consisted of a pipe with endcaps and a 3.8 cm long, .63 cm inner diameter nozzle. The furnace was wrapped around the pipe and consisted of ceramic and Canthol, with molybdenum radiation shielding. The furnace was controlled by a PID controller, and was rated at 1 kw.

[p] Lunar regolith simulant is metastably crystalline below about 1200° C. It has been fiberized at Clemson at about 1500° C. Bottle glass can be fiberized at about 1100° C, and its behavior is well understood.

[q] Ball Aerospace, of Denver, Colorado, adapted our dc electric motor for vacuum use by baking out volatiles and relubricating with low vapor pressure grease.

[r] Calcium has a vapor pressure of 1 torr at about 840° C, and 10 torr at about 950° C[7].

[s] The gold was applied in a thin surface layer by sputtering, and alloyed with the crucible platinum by heating in air at 1200° C for an hour.

[t] The regolith simulant had the following composition (weight percent):
SiO_2: 45; Al_2O_3: 27; CaO: 16; MgO: 6.48; FeO: 5.47; TiO_2: trace; MnO_2: 0.18; K_2O: 0.11; Na_2O: 0.11.

u flow = K*(D^4*h) / (l*Viscosity). flow:: volume of glass per unit time passing through bushing; K:: dimensional constant; D:: bushing diameter; h: height of glass in reservoir (head); l:: length of bushing. Note that flow is proportional to the **fourth** power of bushing diameter.

v The damage consisted of Canthol fusion, alloying between Canthol and calcium vapor, reactions between calcium and ceramic, and welding of the endcaps to the pipe. Use of other heating methods and a different container geometry should eliminate the causes of this failure.

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